Journal of Cardiovascular Magnetic Resonance®, 2(3), 201–208 (2000)

Magnetic Resonance Angiography

Four-Dimensional Aortic Blood Flow Patterns in Thoracic Aortic Grafts

Hugo G. Bogren, Michael H. Buonocore, and David M. Follette

Departments of Radiology and Surgery, University of California–Davis, Medical Center, Sacramento, California

ABSTRACT

Time-resolved cardiac gated three-directional velocity data obtained with magnetic resonance velocity-encoded phase contrast sequences were used to study blood flow patterns in thoracic aortic grafts. Twelve patients were studied, 6 with traumatic descending aortic pseudoaneurysms, 3 with atherosclerotic aneurysms, and 3 with dissecting aneurysms. All grafts had an inflow jet; outflow jet; and/or vortices proximal, in, or distal to the graft. Flow abnormalities were generally mild in the descending aortic traumatic pseudoaneurysms seen in young people. The atherosclerotic aneurysms seen in elderly patients had the most abnormal flows with multiple vortices in and outside the graft. Blood persisted up to one and a half heartbeats in some vortices and took three to five heartbeats to flow from ascending to descending aorta compared with two to three in age-matched normal subjects. Rather large energy losses, probably up to 33% of the cardiac output in our worst case, may occur in thoracic aortic grafts.
KEY WORDS: *Atherosclerotic aneurysm; Magnetic resonance velocity mapping, Thoracic aortic grafts; Three-directional aortic blood flow patterns; Traumatic descending aortic pseudoaneurysm.*

INTRODUCTION

More than 200,000 prosthetic vascular grafts are implanted every year in the United States, and much research has been devoted to finding the ideal graft, which has been defined as follows: For a synthetic vascular graft to function as a normal blood vessel, it must contain some or all of the activities and properties, which make natural blood vessels function normally (1). Emphasis has mainly been placed on the endothelial function of the graft and not on its main function to carry normal blood flow. The ability of the graft to carry normal blood flow was studied in four grafts with three-dimensional velocity mapping, including vector mapping (2). The present study extends the previous study to an additional 12 patients with grafts and uses four-dimensional velocity mapping, including particle paths, so that much more detailed information is obtained about the blood flow in the whole volume of the thoracic aorta, including the grafts. We previously studied time resolved three-directional

Received August 12, 1999; Accepted January 26, 2000
Address reprint requests to Hugo G. Bogren.

magnetic resonance velocity fields in the aorta of normal subjects of varying age. To determine normal flow characteristics in the aorta, this study compares these characteristics in grafted patients with those from normal subjects.

DEFINITIONS

The term ''streamline'' refers to a path that is everywhere tangent to the velocity vectors at a particular point in time. It is the path that a particle would take if released into the velocity field with the field held constant. This path would not match the true path of the particle through the vessel because velocity fields in vessels are time varying. A true particle path is everywhere tangent to the velocity vectors at different points in time. When the velocity field is thoroughly time independent, the definition of particle path and streamline are identical. Vector maps are two-directional snap shots of blood flow at a particular time in one slice only.

A vortex refers to a collection of particles that revolve around a point. A vortex can be a single loop or can be sustained, meaning that the particles make several revolutions around the point. The vorticity can be quantified as well as the energy loss in a vortex (4). Helical or spiral flow refers to collections of particles that revolve around an axis and also have a net forward velocity parallel to the direction of the axis. Helicity can be quantified, as can the energy loss in a helix (4).

METHODS

Cardiac gated three-dimensional velocity encoded phase data sets were acquired using sequential two-dimensional data acquisitions in a sagittal oblique orientation through the thoracic aorta with TR 28 msec, TE 8.8 msec, flip angle 30 degrees, matrix 128 × 256, NEX 1–2, field of view 36–40 cm, slice 6 mm, skip - 3 mm (meaning that slice centers were spaced 3 mm apart), number of slices 12–15, scan time 3–4 min per slice, four-point all-direction velocity encoding, encoding value 180–250 cm/sec, time resolution 112 msec, body coil for radiofrequency transmission and reception, flow compensation on, phase difference analysis on. All studies were performed on a GE Signa Advantage MR system, version 5.4.3 with postprocessing algorithms for gradient interpolation and phase correction turned off. For details see reference 5. The localization and specification of the sagittal oblique slices is shown in Fig. 1.

Software programs were developed for processing, analysis and display of the blood velocities from these large data sets. The ''MRI View'' program (4) was developed on a Silicon Graphics Indigo Elan workstation in C, GL, X Window System, and Motif. Using this program, data could be displayed in cross-sectional or three-dimensional perspective view. In the three-dimensional perspective view, there was full rotational, zoom, and clipping plane capability of the scene, which could be composed of vessel boundaries derived from amplitude images and flow representations. Particle paths were computed by forward and backward time integration of the velocity field, starting from any user-defined region. Arrow maps were computed as short-duration (typically 8 msec of forward integration) particle paths starting from uniformly spaced points over the lumen volume. Numerical criteria, computed for each path, were used to automatically terminate the path under specific conditions, such as when the path exited the vessel and entered a region of high divergence of the velocity vector field. Particle paths could be started from a fixed region at each time point in the cardiac cycle to reveal, in a movie loop, the continuity of flow through the region, the so-called ''all-times'' display. Color coding of the paths was used to display the instantaneous speed, the time of arrival relative to the starting point of the particle path, or the absolute time within the cardiac cycle.

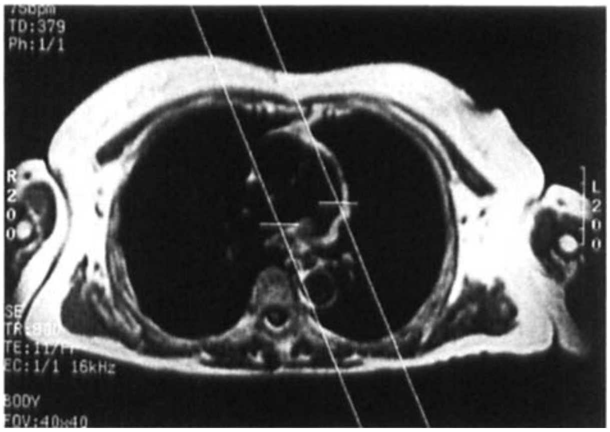

Figure 1. Axial spin echo image of the chest at the level of the pulmonary artery bifurcation. Ten to 15 overlapping slices were taken between the white lines covering all of the thoracic aorta.

Twelve patients were studied, 6 with traumatic descending aortic pseudoaneurysms (average age, 33 yr), 3 with atherosclerotic aneurysm (average age, 71 yr), and 3 with dissecting aneurysms (average age, 48 yr) (Table 1). All were repaired using an interposition Dacron graft impregnated with albumin (Hemashield Hemofil Meadox [0.1 P], knitted without albumin or woven).

Table 1

Case Series

Patient	Sex	Age (yr)	Aneurysm	Method of Diagnosis	Graft	Time from Surgery	Flow	Abnormal Flow Degree	Miscellaneous
TN	M	38	Type A Diss 4+ AI	CT TEE	Hemofil CABG ×2	1.13 d 2.3 mo	13 days after surgery. Very irregular chaotic slow flow, jet and vortices 3 months after surgery. Less irregular, faster flow, vortices	5 3	Amphetamine abuse
JW	M	40	Type B Diss	Angio MR	Albuminoid #22	2 yr, 5 mo	Very irregular flow in AA and Arch with vortices into the graft. Graft not well visualized	3	Hypertension, claustrophobia
LS	F	65	Type B Diss	CT	Hemashield #24	1 yr, 4 mo	AA vortex. Jet into graft. Slow flow in graft 20–30 cm/sec. Takes 4 HB to DA, 2 HB in graft. Vortex in graft	5	Also abdominal aneurysm
LB	M	62	DA Athr An	CT	Hemashield #18	2 yr	Jets 80 cm/sec in and out of graft. Chaotic in graft. 4 HB to DA. Graft flow 40 cm/sec	5	Treated hypertension Hypercholesterolemia
M MC	F	75	AA Athr An	CT	Knitted #24	4 yr, 4 mo	3 vortices in graft, one distal to graft Residence time up to 2 HB (see Fig. 3)	5	2+ AI HT Hyperlipidemia Smoker
JR	M	75	DA Athr An	CT	36-mm Dacron woven	5 yr, 4 mo	Very slow flow in graft 5–20 cm/sec 40 cm/sec in AA 4–5 HB to DA. Multiple vortices in graft with residence time of 1 HB in each	5	History of myocardial infarction. Status postsurgery for abdominal aneurysm

Table 1

Continued

Patient	Sex	Age (yr)	Aneurysm	Method of Diagnosis	Graft	Time from Surgery	Flow	Abnormal Flow Degree	Miscellaneous
SL	M	24	DA traumatic pseudoaneurysm	Angio	Hemashield 18 mm	3 yr, 2 mo	Stenotic proximal anastomosis. Jet into graft. 120 cm/sec and out of graft 100 cm/sec Vortex in AA and graft	3	
DC	M	30	DA traumatic pseudoaneurysm	Angio	Hemashield 18 mm	4 mo	Narrow proximal anastomasis with jet. Vortex in Arch and in graft	3	
RC	M	31	DA traumatic pseudoaneurysm	Angio	Hemashield 16 mm	2 yr, 4 mo	Jet into graft. Vortex in graft	2	
JV	M	32	DA traumatic pseudoaneurysm	Angio	Hemashield 16 mm	1.5 yr	Proximal stenosis with jet. Irregular flow with turbulence, vortices in graft, and distal to graft. Residence time 1 HB	5	
M	F	37	DA traumatic pseudoaneurysm	Angio	Hemashield 20 mm	4 yr	Proximal and distal stenosis with jets. 1.5 m/sec, 70–80 cm/s in graft. Irregular flow in graft	2	
SS	F	45	DA traumatic psuedoaneurysm	Angio	Hemashield 18 mm	2 mo	Jet in and out 100 cm/sec, 1 HB to DA 80 cm/sec (see Fig. 2)	2	

AA, ascending aorta; AI, aortic insufficiency; An, aneurysm; Arch, aortic arch; Athr, Atherosclerotic; CABG, coronary artery bypass grafting; CT, computed tomography; DA, descending aorta; Diss, dissection; HB, heart beat; HT, hypertension; MR, magnetic resonance.

Table 2

Case Series: Summary of Results

	Trauma	Atherosclerosis	Dissection
n	6 (in DA)	3 (2 in DA, 1 in AA)	3 (1 in AA, 2 in DA)
Age (yr)	33 (24–45)	71 (62–75)	48 (38–65)
Sex	4 M, 2 F	2 M, 1 F	2 M
Graft	Hemashield	1 Hemashield 1 Knitted 1 Dacron	1 Hemashield 1 Hemofil 1 Albuminoid
Time to study	2 yr (2 mo–3 yr)	3 yr, 3 mo (1–5 yr)	13 days–2 ½ yr
Abnormal flow	3/5	5/5	4/5

AA, ascending aorta; DA, descending aorta.

RESULTS

Results are shown in Tables 1 and 2. The younger group with traumatic pseudoaneurysms had flow that differed less from normal subjects of the same age than the elderly patients with atherosclerosis or dissection. (For flows in age-matched normal subjects, see Figs. 2–5 in ref. 3.) However, all patients had abnormal flow; the least abnormal was acceleration and jet formation into the graft in the descending aorta and/or out of the graft (grade 1). Two patients had vortices in the graft (grade 2; Fig. 2). The same degree of abnormality was seen in one patient 2 months after grafting and in one patient 4 yr after. The abnormal flow was classified as five grades of abnormality: 1+, acceleration; 2+, acceleration and one vortex; 3+, two vortices; 4+, vortices proximal, in, and distal to graft; 5+, multiple vortices or chaotic flow with one heartbeat or longer particle residence time.

The three patients, two men and one woman, with atherosclerotic ascending or descending aortic graft replacement were elderly (average age, 71 yr), with one Hemashield, one knitted, and one woven Dacron graft. The Hemashield graft had highly irregular flow with vortices very similar to the knitted and the Dacron graft. The flow was severely abnormal in all cases whether the study took place 2 or 5 yr after surgery (Fig. 3) (compare normal flows in Figs. 2–5 in ref. 3).

The three patients with dissection had an average age of 48 and comprised one woman and two men. All had highly disturbed flow. One patient was studied 13 days after surgery when the flow in his ascending aortic graft was extremely irregular with vortices and chaotic flow (grade 5). He was restudied 3 months later when he had two vortices and was classified as grade 3 abnormal flow. Two patients, one grade 3 and one grade 5, were studied 1.25 to 2.5 yr after the surgery and had abnormal flow as well.

DISCUSSION

Bogren et al. (2) examined four patients with aortic grafts using magnetic resonance velocity vector mapping, which combines two directions into a vector and a separate acquisition of a third direction. However, the acquisitions were obtained in one slice only, in the middle of the grafts. The detailed flow in and out of the grafts could, therefore, not be seen over the whole volume of the graft. The great advantage with the present time resolved three-directional technique is that we can see exactly how the blood comes into the graft, how it behaves in the whole volume of the graft, and how it leaves the graft. The vector maps give the impression of being time resolved but are not. They are only snapshots of the flow in the various parts of the slice of the aorta during the cardiac phase that is displayed. Vector maps can be shown in cine-mode but with no special advantage. However, our study with vector maps showed abnormal flow in the grafts and gave us incentive to do the present study.

The ideal graft should contain some or all of the activities and properties that make natural blood vessels function normally (1). The ideal properties have been focused on the endothelial functions, and very little emphasis has been placed on the prime function of a blood vessel (i.e., to carry blood flow). Some emphasis has been placed on the hemodynamics of grafts (6), but the tool to study the flow in grafts in detail has not been available until now. The results of our study are that no investigated graft mate-

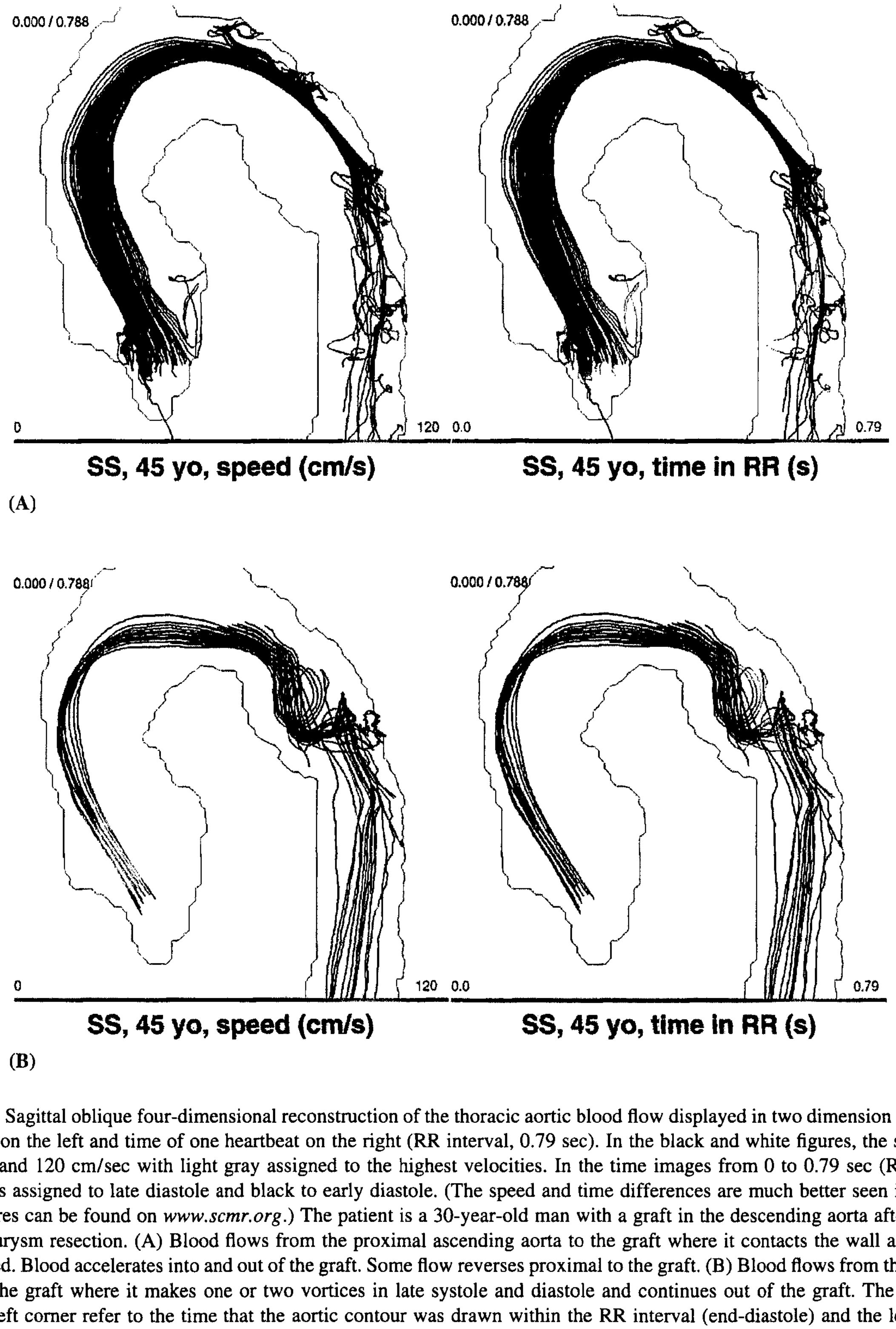

Figure 2. Sagittal oblique four-dimensional reconstruction of the thoracic aortic blood flow displayed in two dimension with velocities shown on the left and time of one heartbeat on the right (RR interval, 0.79 sec). In the black and white figures, the speed varies between 0 and 120 cm/sec with light gray assigned to the highest velocities. In the time images from 0 to 0.79 sec (RR interval), light gray is assigned to late diastole and black to early diastole. (The speed and time differences are much better seen in color and color pictures can be found on *www.scmr.org*.) The patient is a 30-year-old man with a graft in the descending aorta after traumatic pseudoaneurysm resection. (A) Blood flows from the proximal ascending aorta to the graft where it contacts the wall and becomes disorganized. Blood accelerates into and out of the graft. Some flow reverses proximal to the graft. (B) Blood flows from the ascending aorta into the graft where it makes one or two vortices in late systole and diastole and continues out of the graft. The numbers in the upper left corner refer to the time that the aortic contour was drawn within the RR interval (end-diastole) and the length of the interval, which was 0.788 sec.

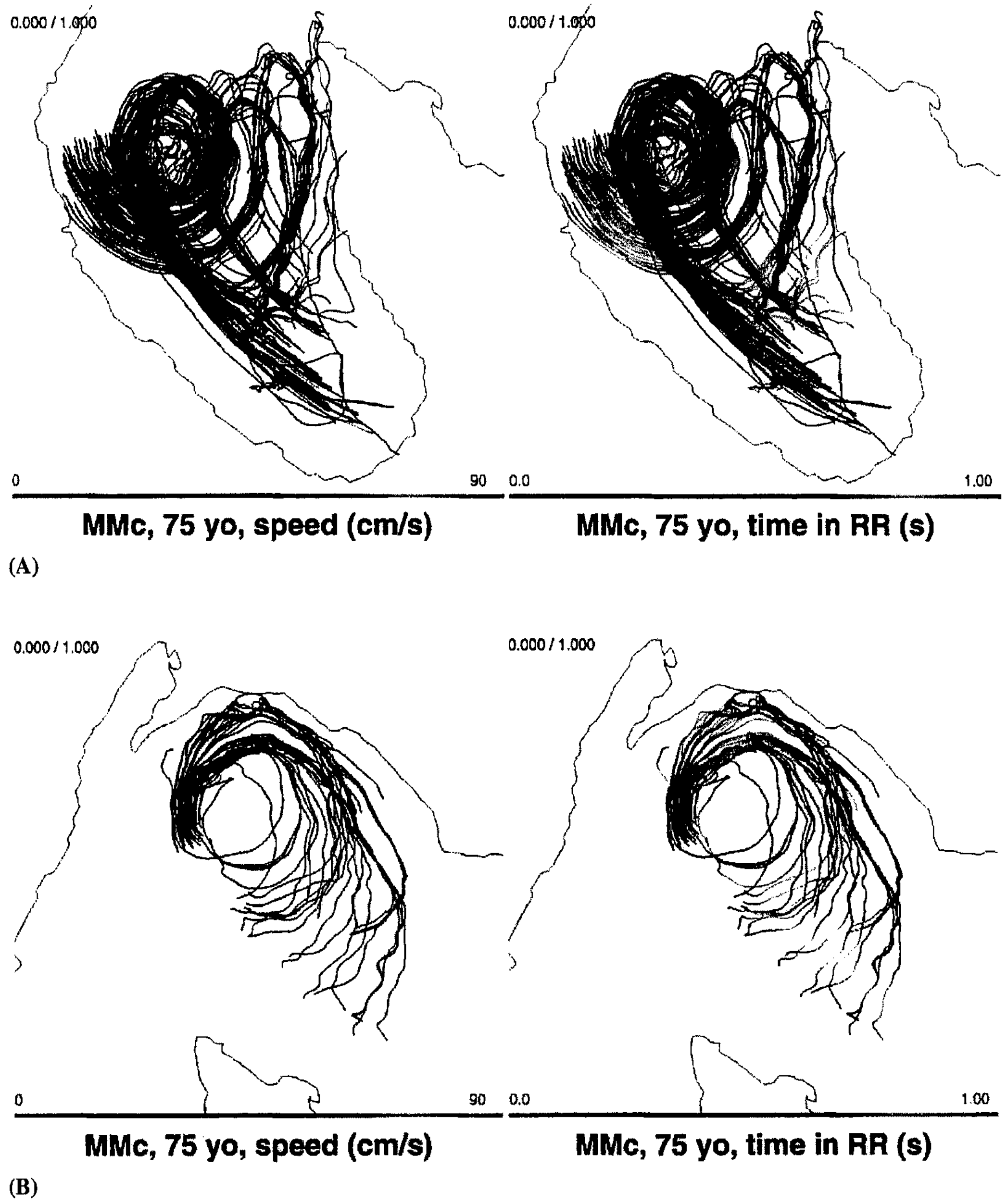

Figure 3. A 75-year-old woman with an ascending aortic graft (same display as in Fig. 2). In the black and white figures, the speed varies between 0 and 120 cm/sec with light gray assigned to the highest velocities. In the time images from 0 to 0.79 sec (RR interval), light gray is assigned to late diastole and black to early diastole. (The speed and time differences are much better seen in color and color pictures can be found on *www.scmr.org*.) Blood flowed in a large helix proximal to the aortic graft (A), flowed into the graft, went into a second helix, and then out of the graft into a third helix (B). The particle residence time in the third helix was up to one and a half heart beats. The numbers in the upper left corner refer to the time that the aortic contour was drawn within the RR interval (end-diastole) and the length of the interval, which was 1 sec.

rial carried normal blood flow and that further research with new perhaps compliant materials is warranted.

Although graft replacement of aortic aneurysms and pseudoaneurysms is life-saving and grafts have many morphologic and metabolic functions that are similar to normal vessels, we found that they all are associated with abnormal blood flow that may result in energy losses. We estimated that up to one third of cardiac energy may have been lost in a poorly functioning graft with particle residence time of 1.5 heart beats (4), as was seen in one of the grafts (Fig. 3). The flows in the descending aortic grafts in the young population with traumatic pseudoaneurysms were mildly to moderately disturbed (average, grade 3), but the flows in the grafts in the atherosclerotic and dissecting aneurysms cases were severely disturbed (grades 4 and 5). The grafts in the young populations are supposed to last up to 50 years, and it is the hope of the surgeon that the flow in them will not deteriorate. There is great risk that the flows in the grafts will become more irregular after many years of use, perhaps due to dilation, and they can certainly be influenced by vascular senescent changes. The irregular flow with energy losses in the elderly people is unfortunate because they already have senescent changes with irregular flows and energy losses (3) and cannot afford further deterioration of flow. Again, further studies into new graft material and anastomosis technique are called for until a more ideal prosthetic vascular graft material and shape has been found.

The graft must have the same transverse area and shape as the aorta, which may be different in the proximal compared with the distal anastomosis. The graft also must have the same curvature as the replaced aorta had before it became aneurysmatic. Graft length may be an issue. Posttraumatic repairs generally require very short grafts (1–3 inches), whereas repair of dissection and atherosclerotic aneurysm generally requires longer grafts (4–8 inches). The most abnormal flows were seen in elderly people, where the quality of the vessel that comes into and out of the graft is less than in young patients, and the grafts are generally longer. Also, the same graft material may not suite all ages. Both issues need to be studied further.

LIMITATIONS OF THE STUDY

Possible errors have been described in a previous article (3). No detailed error analysis has been performed by anyone and was not considered necessary for the purpose of this article.

Particle paths that moved within one pixel of the defined aortic wall were affected by the velocity measurement having relatively larger errors and had a high likelihood of exiting the vessel. For that reason, any path that reached one pixel beyond the edge of the defined intraluminal region was terminated at the location. This typically occurred in diastole when the velocities were low. With respect to the irregular flow patterns shown in the grafts and their grading, the particle paths had not passed near the vessel wall before the time when the particle paths were displayed. Consequently, these measurements were not affected by any additional velocity errors that existed at the vessel wall. The conclusions drawn from the data were selective, respecting the possibility of systematic errors in the velocity data. Conclusions involving subtle characteristics of the flow patterns that would strongly be influenced by systematic errors were not formed.

CONCLUSIONS

All grafts were found to have abnormal flow. The least abnormal flow was seen in young patients who had descending aortic grafts secondary to traumatic pseudoaneurysms. Graft replacement in middle-aged or elderly people due to aortic dissection or atherosclerotic aneurysm had highly abnormal flows.

REFERENCES

1. Didisheim P. Current status of biomaterials: use and development. In: Hwang NHC, Tutto VT, Yen MRT, eds. *Advances in Cardiovascular Engineering*. New York and London: Plenum Press, 1992:189–195.
2. Bogren HG, Mohiaddin RH, Yang GZ, Kilner PJ and Firmin DN. Magnetic resonance velocity vector mapping of blood flow in thoracic aortic aneurysms and grafts. *J Thorac Cardiovasc Surg*, 1995;110:704–714.
3. Bogren HG and Buonocore MH. four-dimensional magnetic resonance velocity mapping of blood flow patterns in the aorta in young vs. elderly normal subjects. *J Magn Reson Imaging*, 1999; 10:861–869.
4. Saffman PG. *Vortex Dynamics*. Cambridge: Cambridge University Press, 1992:1–73.
5. Buonocore MH. Visualizing blood flow patterns using streamlines, arrows, and particle paths. *Magn Reson Med*, 1998; 40:210–226.
6. Phifer TJ and Hwang NHC. Vascular grafts: clinical and hemodynamic applications. In: Hwang NHC, Tutto VT, Yen MRT, eds. *Advances in Cardiovascular Engineering*. New York and London: Plenum Press, 1992:385–400.